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Experiments and simulations on heat exchangers in thermoelectric generator for automotive application

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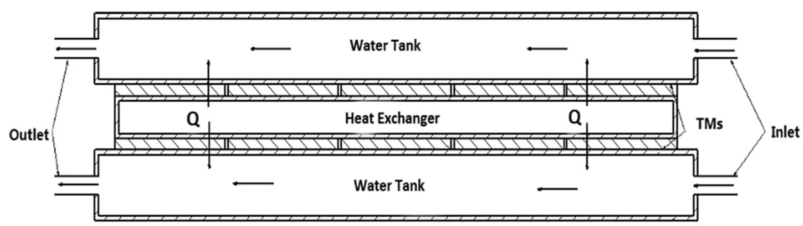
HIGHLIGHTS

- Different internal structures and thickness of heat exchangers were proposed.
- Power output testing system of the two heat exchangers was characterized.
- Chaos-shaped heat exchanger (5 mm thickness) shows better performance.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, an energy-harvesting system which extracts heat from an automotive exhaust pipe and turns the heat into electricity by using thermoelectric power generators (TEGs) was built. Experiments show that the temperature difference in automotive system is not constant, especially the heat exchanger, which cannot provide the thermoelectric modules (TMs) large amount of heat. The thermal performance of different heat exchangers in exhaust-based TEGs is studied in this work, and the thermal characteristics of heat exchangers with different internal structures and thickness are discussed, to obtain higher interface temperature and thermal uniformity. Following computational fluid dynamics simulations, infrared experiments and output power testing system are carried out on a high-performance production engine with a dynamometer. Results show that a plate-shaped heat exchanger with chaos-shaped internal structure and thickness of 5 mm achieves a relatively ideal thermal performance, which is practically useful to enhance the thermal performance of the TEG, and larger total output power can be thus obtained.

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1. Introduction

Because of the global energy crisis and the environmental protection issues, energy recovery techniques have become significantly demanding for a long time. Some examples of energy recovery techniques are water heat recycling, heat recovery ventilation, heat recovery steam generators, and so on [1]. Waste heat recovery by using thermoelectric power generators (TEGs) is another attempt. TEGs can directly convert thermal energy to electrical energy and have the advantages of light weight, no noise, and no mechanical vibration. Owing to these merits, TEGs have found its potential in many applications, such as space applications, thermal energy sensors, textiles, etc [2–8].

Waste heat from automotive vehicles is considerable as well. For a typical gasoline-engine vehicle, about 40% of the fuel energy is discharged from the exhaust pipe and about 30% is lost into the coolant. The automotive exhaust is low in specific heat and small in time-averaged mass flow rate, so that an efficient heat exchanger is essential to extract heat energy from exhaust when thermoelectric conversation of conventional materials is 5%–7%

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for TEG [9]. Making good use of these waste heats improves the energy efficiency and saves money [10]. Historically, several types of heat exchanger and different heat transfer enhancement measures such as the ribbing, grooving and protrusions have been investigated since the first automobile TEG was built in 1963. Serksnis [11] initially reported a stainless heat exchanger just like the exhaust pipe, no heat transfer enhancements were set in gas side. Birkholz et al. [12] designed a Hastelloy X rectangular heat exchanger with internal fins in exhaust side and an aluminum cold-side heat exchanger. Bass et al. [13] proposed a hexagonal cylinder and a center hollow displacement conic heat-diffuser for Cummins 14L NTC 350 diesel engine, discontinuous swirl fins were installed on surface of the center body to break laminar boundary layer and enhance gas turbulence. Yang [14] indicated that the consumer fuel savings over a three-year period is about \$400 for a 23.5 mpg vehicle, under the assumption of \$2/gallon, 15,000 miles/yr, and a desired 10% fuel-economy improvement (the overall objective raised by the US Department of Energy in 2004). The commonly utilized components in a vehicle for implementing the TEGs are the radiators and the exhaust system. Hsiao et al. [15] attached the TEGs to the waste recovery system than to the radiators which obtains a better performance based on the simulation models and experiments. Chung et al. [16] investigated a thermoelectric energy generation system which used a TEG. The main feature of their study was the use of high temperatures (up to 200 °C) to ensure TEG reliability, especially for diesel engines, whose exhaust gases are as hot as 200 °C–300 °C at the outlet of the catalyst filter. Thacher et al. [17] employed a rectangular, 1018 carbon steel compact heat exchanger with offset strip fins for a 5.3 L V8 gasoline engine. With the same requirements for exhaust heat exchanger in vehicle waste heat recovery by Rankine cycle, a shell and tube counter flow heat exchanger was used with exhaust gases in tubes and working fluids in shell [18]. Hsu et al. [19] [20] constructed a heat exchanger mounted with eight Bi_2Te_3-TEG systems with eight heat sinks, the heat sinks need electricity to drive the air. This system obtains a total 44 W excluding the heat sinks. In 2012, they enlarged the heat exchanger with 24 Bi_2Te_3-TEG systems and added a slopping block in the inlet. A maximum power of 12 W was just obtained. The experimental results surprisingly show that a small-size heat exchanger with less TEGs has a good performance and gets a large output power.

However, according to Hsu's study, the thermal performance of heat exchanger is not good. The heat exchanger needs to be optimized, especially internal structure, adding a slopping block in the inlet is not enough. This paper presents analysis of a large heat exchanger. Regardless of other conditions, such as exhaust condition, cooling condition, and clamping force, raising the interface temperature by improving the heat exchanger will significantly enhance the overall efficiency of the TEG. To take advantage of the electricity generation performance of each thermoelectric module (TM), optimization of the thermal uniformity of the heat exchanger is also vital [21], and a large total power can be thus obtained.

2. Experimental setup

There are three ways of heat transfer: heat convection, heat conduction and heat radiation. Exhaust heat passes to the heat exchanger walls by thermal convection, and then passes to the TMs and water tank walls by heat conduction. Finally, water flow takes the heat away. Every water tank has three surfaces in direct contact with air, so part of heat is dissipated by thermal convection into the atmosphere. This waste heat recovery system is designed for exhaust pipe of automobiles. TMs are clamped with sufficient compressive force between a heat exchanger connected to the exhaust pipe and cooling water tanks in an exhaust-based TEG. Exhaust gas flows into the heat exchanger through a bypass to provide a heat source. The cooling water (engine cooling water) is pumped into the water tanks to form the cold side [22]. Then, electric power is generated due to the temperature difference between the two sides of the modules and to be stored in batteries. The design and simulation of the heat exchanger are mainly described in this article. TMs (Shanghai Institute of Ceramics of the Chinese Academy of Sciences) are arranged on both surfaces of the heat exchanger when the exhaust gas passes by. The schematic diagram of the experimental exhaust waste heat recovery system is illustrated by Fig. 1. Some measuring instruments are equipped to construct this experimental setup. A 2.0-L naturally aspirated engine is used as study object. Its performance data are listed in Table 1. A dynamometer (maximum power input 160 kW, maximum speed 6000 rpm) is also used. Several transducers are used: pressure sensor, K-type thermocouples and infrared camera to record the temperature distribution of the exhaust heat exchanger, TMs and water tanks. A high power electrical load is connected to the system which is used to measure the voltage and power output.

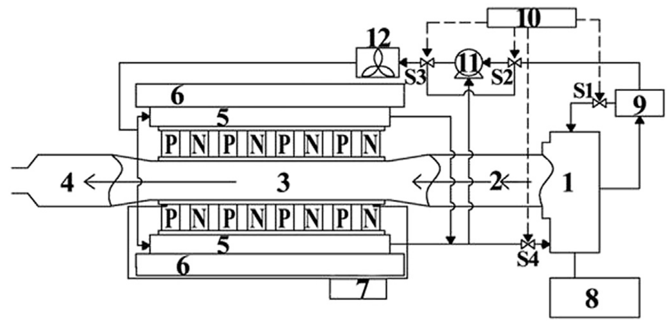

Fig. 1. Schematic diagram of the experimental thermoelectric generator system 1: Automobiles engine. 2: Catalytic converter. 3: Heat exchanger for passing exhaust gas. 4: Muffler. 5: Water tank. 6: Clamping device. 7: Electronic load. 8: Dynamometer. 9: Cooling system. 10: Controller. 11: Water pump. 12: Heat sinks.

Considering the square-shaped TMs, plate-shaped and hexagonal-prism-shaped heat exchangers meet the requirement. However, the distance between chassis and ground is short and the height of plated-shaped heat exchanger is also short, which is benefit for the arrangement of TMs, so the plate-shaped heat exchanger is more suitable for TEG application. Fig. 2 shows a plate-shaped heat exchanger, its TEG system and bench test. The plate-shaped heat exchanger of TEG is connected to the exhaust pipe of diameter 36 mm on both sides. The section of the plate-shaped exchanger is a 400-mm-long by 290-mm-wide rectangle, its height is just 18 mm. There are 60 TMs placing on front and back surface of heat exchanger.

Table 1
The engine performance parameters.

Parameter	Value	Parameter	Value
Cylinder number	4	Governed Power (kW)	108
Valves per cylinder	4	Governed speed (rpm)	6000
Displacement	1997 ml	Peak torque/speed	200 N m/4000 rpm
Bore/stroke (mm)	85/88 mm	Power of pump	0.18kw
Firing order	1-3-4-2	Cooling mode	Water Cooling
Radiator size	547 × 415 × 50 mm	Number of fan shift	1

Fig. 2. Concept of the system architecture: (a) TEG system model, (b) infrared experiment and (c) TEG system to test output power.

Table 2 lists the boundary conditions and dimensions of each element used in this work. As the heat exchanger, the inlet boundary condition is a uniform flow of velocity 15.2 m/s and temperature is 350 °C, which is measured when the engine revolutions were maintained at around 3000 rpm, other conditions, such as TMs, cooling condition and clamping force is unchanged. The geometric features and transport properties of the PN materials used in this work are listed in Table 3. In subsequent analysis without special description, values are taken from Tables 2 and 3.

Table 2
Boundary parameters.

Parameter	Value
Engine revolution	3000 r/min
Exhaust inlet temperature T_f	350 °C
Exhaust flow speed	15.2 (m/s)
Each module's area A	0.050 * 0.050 (m^2)
Total area	0.400 * 0.300 (m^2)
Ambient temperature	25 °C
Ambient heat transfer coefficient	15 (W/(m^2 • K))
Material of heat exchanger	Brass
Dimension of heat exchanger (mm^3)	400 * 290 * 18 (h)
Material of water tank	Aluminum
Number of water tank	12
Dimension of water tank (mm^3)	300 * 60 * 21 (h)
Thickness of water tank	3 (mm)
Flow rate of water	9.27 L/min
Cooling water temperature	90 °C (engine water)
Material of clamping device	Steel

3. Simulation of the thermal field of the heat exchanger

3.1. Simulation model

As is shown in Fig. 3, the plate-shaped heat exchanger of TEG is connected to the exhaust pipe of diameter 36 mm on both sides. The section of the plate-shaped exchanger of 5 mm thickness is a 400-mm-long by 290-mm-wide rectangle. There are 60 TMs placing on front and back surface of heat exchanger, 5 TMs in a row and totally 6 rows in the front surface, back surface is the same with the front.

The realizable k-ε turbulence model was adopted, in which the dissipation rate equation is derived from the dynamic equation of the mean-square vorticity fluctuation at large turbulent Reynolds number [23]. The convergence criteria adopted herein are a scaled residual under 10^{-3} for the momentum balance, 10^{-6} for the energy balance, and a relative error under 0.1% for the total energy conservation of the system. The no-slip boundary conditions are imposed at all the solid walls. As illustrated in Tables 2 and 3, the inlet boundary condition is a uniform flow of velocity 15.2 m/s and temperature is 350 °C. The exit of the exchanger is connected to the entrance of the rear muffler, whose exit is connected to atmosphere. Imposed at the outlet boundary are zero gradients for velocity and temperature. Additionally, brass has good performance of heat conductivity and heat convection. The heat exchangers are made of brass, so the coefficient of convective heat transfer between the outer surface of the exchanger and the air is set to 15 W/(m^2 • K). For convenience, we adopt a fixed value of convection heat transfer coefficient $h = 15$ W/(m^2 • K) in all the simulations. Finally, the exhaust gas was modeled as air whose properties vary with temperature.

Table 3
Parameters of PN materials.

Parameter	P type	N type
Seebeck coefficient S^j	40 + 0.20T (μV/K)	40 + 0.20T (μV/K)
Electrical resistivity q^j	1.04 × 10^{-5} (Ωm)	1.04 × 10^{-5} (Ωm)
Thermal conductivity k^j	1.5 (W/(mK))	2.5 (W/(mK))
Z	0.2 × 10^{-3} (K^{-1})	2.85 × 10^{-3} (K^{-1})
Height H	0.005 (m)	0.005 (m)

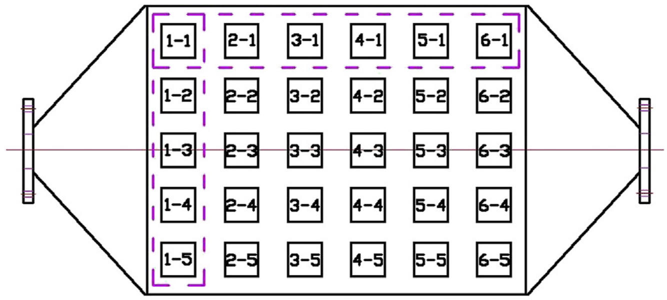

Fig. 3. Arrangement of TMs on the heat exchanger.

3.2. Interface temperature distribution on heat exchangers with different internal structures

In the previous experiments, the heat exchanger was just an empty box with no internal structure, and the TEG system obtained little output power, only several modules in the middle of heat exchanger produced electricity. Considering the fixed cooling water temperature, the results showed that most of the heat sources were concentrated in the middle part of heat exchanger while only a small part of heat passed through the both sides, so it is worth noting that the simulation of heat exchanger would enhance the further design, and obtain higher and more uniform temperature.

The simulation of the heat exchanger with no internal structures was shown in Fig. 4 (a) and (b), in this case study, the diameter of vehicle exhaust pipe is 36 mm but the heat exchanger of TEG system is designed 290 mm in width. There is a sudden expansion as exhaust flow through the exhaust pipe into the system, which leads to an uneven thermal distribution inside the heat exchanger, so the high-temperature region is mainly concentrated in the front of the heat exchanger. The general temperature distribution is not even, with low temperature at the middle and the end. Moreover, the temperature of part of the heat is only 144 °C. It is obvious that the heat exchanger cannot meet the requirement.

Based on the theories of thermal convection, heat conduction and turbulent flow as mentioned earlier, two three-dimensional models of heat exchangers with different internal structures were designed by arranging internal baffles. Fig. 5a, b shows the block diagram of two heat exchangers with different internal structures which extracts waste heat energy. There are called fishbone-shaped and chaos-shaped heat exchangers. The CFD simulation results are shown in Fig. 6a–d. Two heat exchangers have some internal structure in common: there are both two small fins set at the entrance for diverting the flow, so that the high-temperature exhaust gas is diffused in the entire lateral area rather than concentrating in the central region; some fins are disorderly set in the internal structure for disturbing the flow, so that the exhaust gas can be fully in contact with the metal walls of the heat exchanger and stays longer in the cavity of the heat exchanger [24], which can increase the heat that airflow transfers to the fins. There are also some differences: the fishbone-shaped heat exchanger uses 14 fins of 80–130 mm in length while chaos-shaped uses a lot of small fins of 20–35 mm in length; Taking into account the difficulty of casting, the small fins used in chaos-shaped heat exchanger are 10 mm in width while there are 3 mm in fishbone-shaped.

As indicated by the simulation results, the chaos-shape has slightly higher interface temperature at the inlet, and much higher at the outlet and middle. The temperature of outlet of the chaos-shaped heat exchanger is 220 °C on average while the fishbone-shaped is only 190 °C, so the performance of TMs at the outlet is expected to get improved. Moreover, the chaos design shows better uniformity, especially in vertical direction, which facilitates the arrangement of 5 TMs in a row. Fig. 6(b) and (d) also show that the chaos-shaped heat exchanger is filled with streamlines, and fishbone-shaped exists large area that the streamlines do not pass. During simulations, the ambient temperature is assigned for 25 °C. However, heat may accumulate in the system and the ambient temperature would increase for a short period of time. Regardless of this transient phenomenon, Fig. 6 is captured in steady state operational results. Thus, the heat exchanger with chaos internal shape is more ideal for TEG application.

3.3. Interface temperature distribution on heat exchangers of different thickness

Additionally, the thickness of the heat exchanger affects its thermal performance. Heat exchanger thickness of 3 mm, 5 mm, and 8 mm were taken for simulation comparison, using the chaos-shaped structure and the same boundary conditions. Three-dimensional models of the heat exchanger with different thickness were designed. The simulation results are shown in Fig. 7a–c. In these simulation results, figures show a low temperature area in the outlet of heat exchanger of 3 mm thickness, the temperature is proximately 180 °C in this area, which is not expected to be the hot side of our TMs. On the other hand, 5 mm and 8 mm heat exchangers show better uniformity, the average surface temperature is over 250 °C, so the 3 mm cannot meet the needs of arrangement of TMs. Comparing Fig. 7b with Fig. 7c, the interface temperatures of the 5 mm and 8 mm exchangers show little difference, the temperature distribution is almost the same. Considering the vehicle weight, the smaller the thickness, the lighter TEG can be arranged on the vehicle, which largely reduces the vehicle weight and fuel consumption. The practical effect of a 5 mm thickness heat exchanger is therefore better.

4. Results and discussion

4.1. Infrared experiment of different internal structures

A thermal imaging system was used to image the interface temperature distribution on heat exchangers. Pictures of the

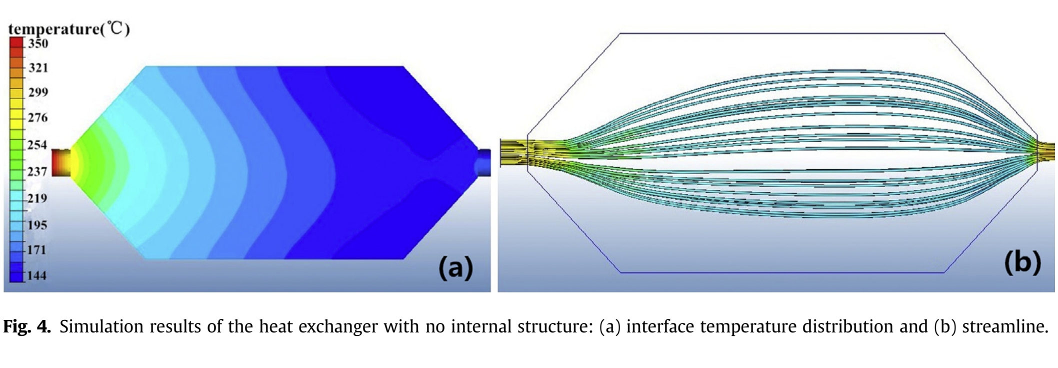

Fig. 4. Simulation results of the heat exchanger with no internal structure: (a) interface temperature distribution and (b) streamline.

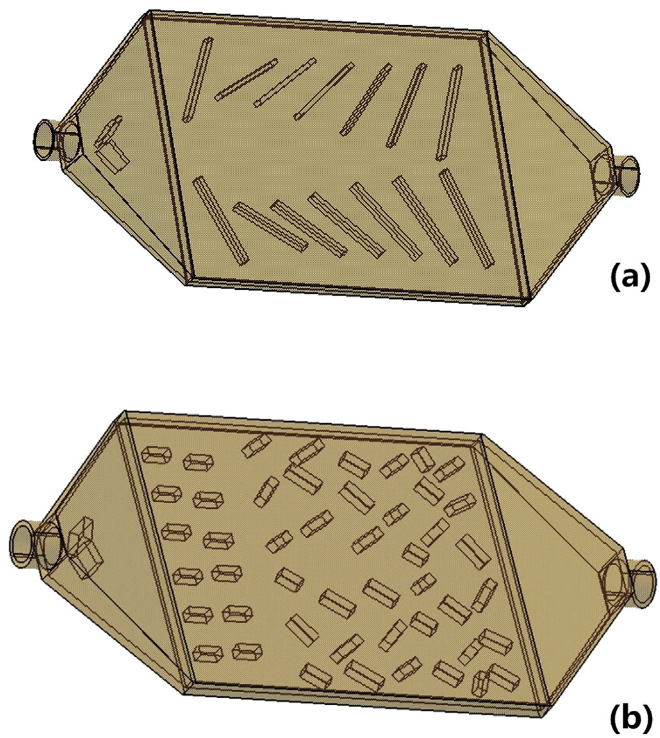

Fig. 5. Block diagram of (a) fishbone-shaped heat exchanger and (b) chaos-shaped heat exchanger.

surface temperature distribution on the heat exchangers with the two internal structures with the fishbone and chaos shape were taken using the thermal imaging system, and compared in Fig. 8a, b. Both heat exchangers are made of brass of 5 mm thickness. In the bench test, the experiment conditions such as the room temperature, wind speed, etc. remained unchanged.

In terms of the surface temperature and uniformity of the whole temperature distribution, it is obvious that the experimental results for these two kinds of structure are in accordance with the simulation results. Besides, the heat exchanger with the fishbone-shaped structure has a slightly higher maximum temperature of

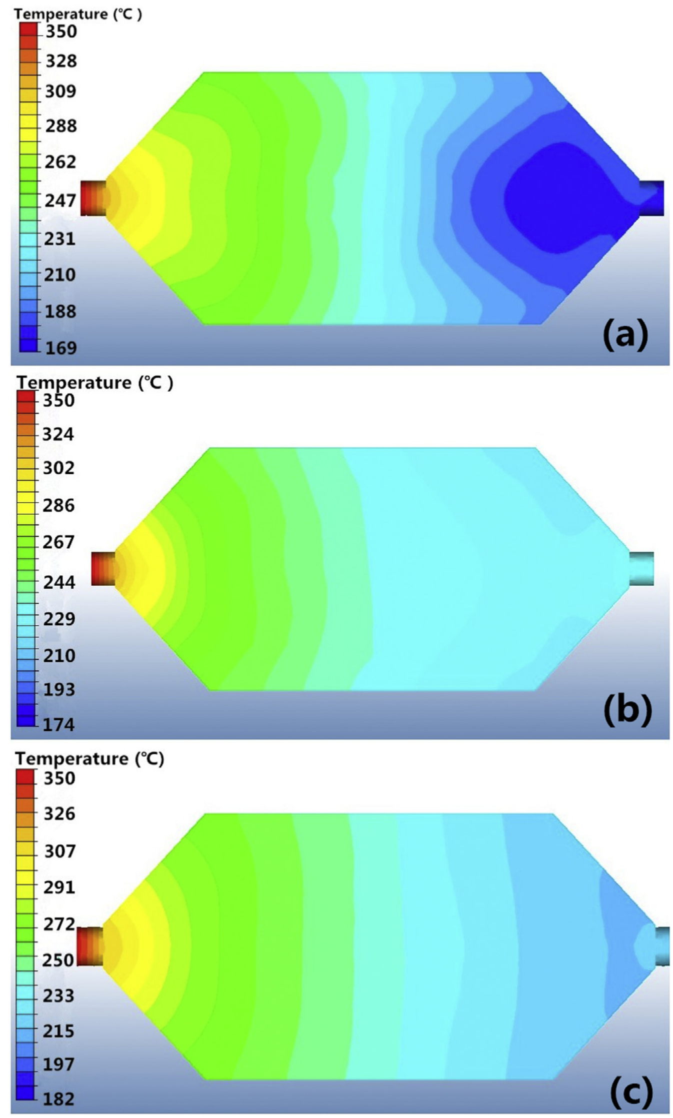

Fig. 7. Simulation results of the heat exchanger with (a) 3 mm, (b) 5 mm, and (c) 8 mm thickness.

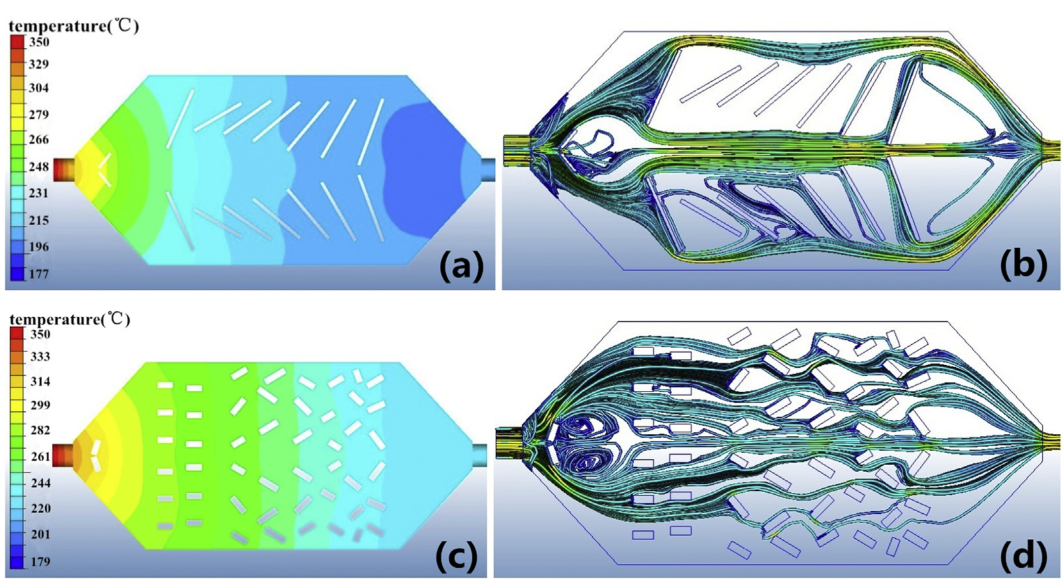

Fig. 6. Simulation results of the heat exchanger with fishbone shape: (a) interface temperature distribution and (b) streamline, chaos shape: (c) interface temperature distribution and (d) streamline.

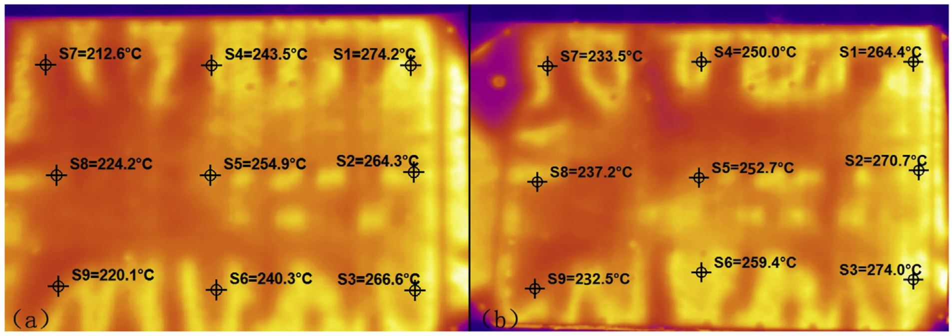

Fig. 8. Infrared experimental results of the heat exchanger with (a) fishbone-shaped and (b) chaos-shaped internal structure.

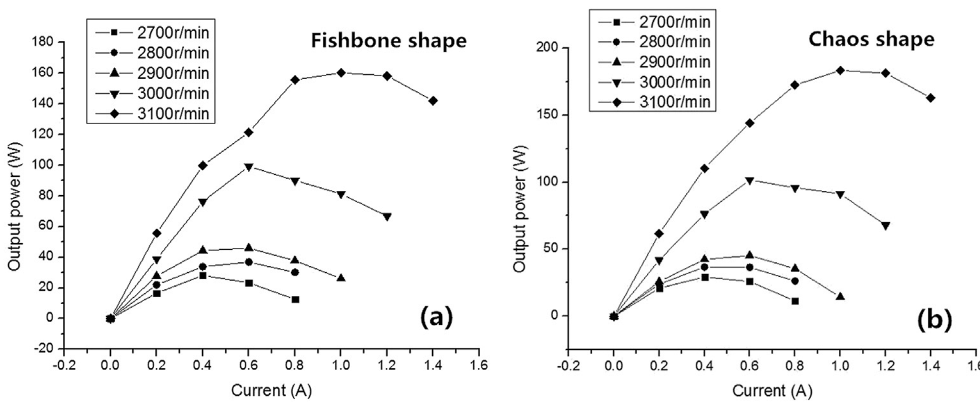

Fig. 9. Curves of output power-current for different engine revolution with (a) fishbone-shaped and (b) chaos-shaped internal structure.

274.2 °C. However, it exhibits remarkable temperature differences between its front and rear end, and the temperature in rear end is much lower than the chaos-shaped heat exchanger. The heat exchanger with the chaos-shaped structure has a relatively higher average temperature, and it is well distributed. Overall, the latter tends to be adopted in the following research.

4.2. System performance testing

To further verify this conclusion, 60 pieces of TMs were placed on the front and back surface of the heat exchanger, aiming at testing the power output of the modules by an electronic load. Both experiments were carried out under the same external conditions, including the cooling conditions, engine, TMs, clamping device and ambient temperature. The only difference is the internal structure of heat exchanger. The results in Fig. 9a, b shows the curves of output power versus current for different engine revolution, and the engine revolution is from 2700 to 3100 r/min. A comparison of the power output between different engine revolutions indicates that for an engine rate less than 2900 rpm, the output power is very poor, but for an engine rate greater than 3000 rpm, the value sharp increases. The trend of the two pictures is consistent. The maximum electrical power output of fishbone-shaped TEG is 160.21 W while the chaos-shaped is 183.24 W. In conclusion, the total output power is higher for the chaos-shaped heat exchanger, which is more ideal for TEG application.

5. Conclusions

Considering the agreement between the experimental results and the CFD flow simulation results, a heat exchanger with chaos shape and thickness of 5 mm is selected to form the hot side. It can reduce the resistance to exhaust heat conduction and obtain a relatively high surface temperature and ideal temperature uniformity to improve the efficiency of the TEG.

This study focuses on structural design of the heat exchanger to improve the efficiency of automotive exhaust heat recovery. Actually, the thermal conductivity of TMs discourages the effective establishment of temperature differences. In future study, the method of simulation modeling with infrared experimental verification introduced herein needs to be combined with heat transfer theory and materialogy to serve for further structural design and optimization of TMs and TEGs to improve the overall exhaust heat utilization and enhance the power generation. To concern the optimization design, energy conversion efficiency and system power capacity that would be very important for prototype vehicle in next generation.

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